

Study of Gamma Irradiated P-type Silicon Diodes with Different Resistivities

Iveta Zatočilová^{1,2}

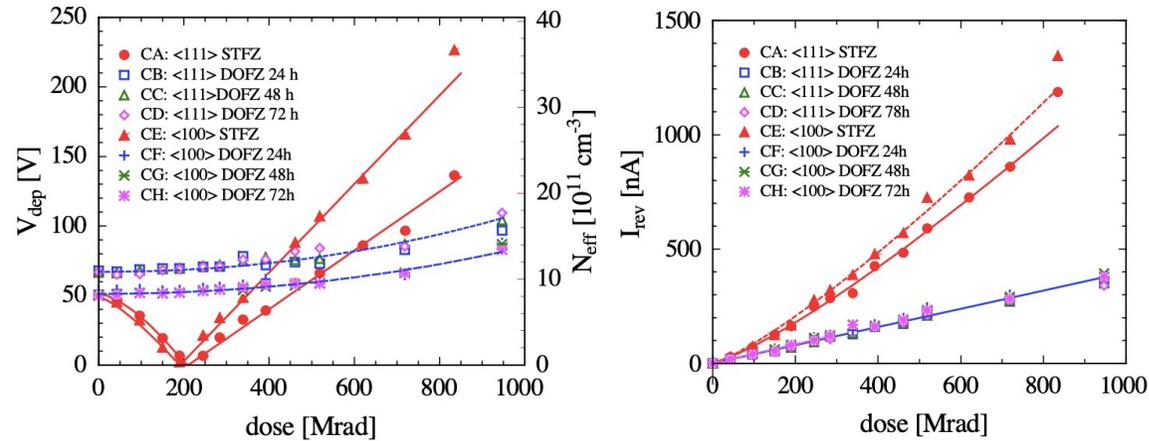
Marcela Mikeščíková¹, Věra Latoňová^{1,2}
Jiří Kroll¹, Radek Přivara³, Denis Dudáš⁴
Jiří Kvasnička¹, Pavla Federičová¹

iveta.zatocilova@cern.ch

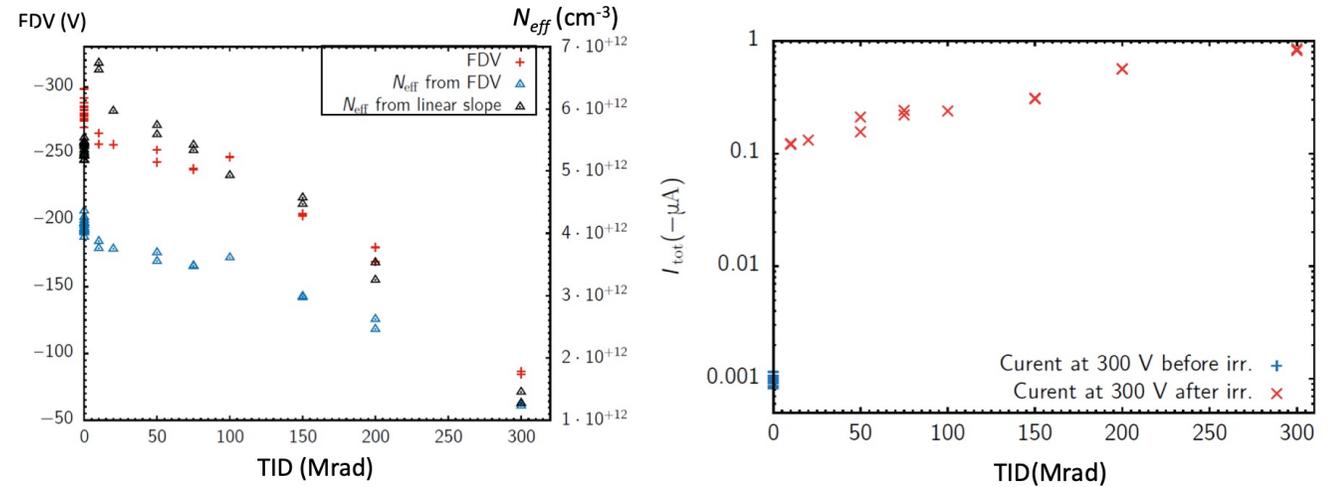
Motivation

- Most of the previous studies of bulk damage caused ^{60}Co gamma in n-type silicon
- A lack of studies of gamma irradiated high resistivity p-type silicon

n-type silicon



p-type silicon



- STFZ – space charge type inversion at 200 Mrad
- DOFZ – non-linear increase of the N_{eff}

- Irradiation of HPK strip sensors for ATLAS ITk
- Decrease in FDV and N_{eff} observed up to 300 Mrad

Measured Diodes

- n-in-p standard float zone diodes from different manufactures
- Comparable active areas and thickness but different silicon resistivities
- Contactable guard ring that enables separation of leakage and guard current $I_{\text{tot}} = I_{\text{leak}} + I_{\text{guard}}$
 - **CNM** 7439 – 5 pcs
 - **HPK** ATLAS17-SPL-MINI VPX29549 – 8 pcs
 - **IFX** MD8 & MD8.4 – 5 pcs



	CNM	HPK	IFX
Active thickness d	285 μm	290 μm	285 μm
Active area A	50.17 mm^2	51.55 mm^2	49.95 mm^2
Active volume V	0.0143 cm^3	0.0149 cm^3	0.0142 cm^3
Measured FDV of unirradiated diode	(36.9 \pm 8.3) V	(273.4 \pm 10.7) V	(283.6 \pm 12.0) V
Calculated resistivity ρ	(23.975 \pm 4.012) $\text{k}\Omega\cdot\text{cm}$	(3.301 \pm 0.001) $\text{k}\Omega\cdot\text{cm}$	(3.077 \pm 0.001) $\text{k}\Omega\cdot\text{cm}$
Wafer oxygen concentration	N/A	1.5 \cdot 10 ¹⁶ – 6.5 \cdot 10 ¹⁷ atoms/cm ³ *	

Full Depletion Voltage

Determined from interpolation curves of measured CV characteristics

Resistivity calculation

$$\rho = \frac{d^2}{2\epsilon_0\epsilon_{Si}\mu_p FDV}$$

$$\epsilon_0 = 8.85 \cdot 10^{-12} \text{ F} \cdot \text{m}^{-1}$$

$$\epsilon_{Si} = 11.7$$

$$\mu_p = 450 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$$

*values from ATLAS ITk requirements document

IV&CV Measurements

- Measurements performed at probestation, diodes contacted by needles
- During all measurements temperature $T = 21 \pm 2 \text{ }^\circ\text{C}$ and $\text{RH} < 10 \%$
- Measured currents normalized to $20 \text{ }^\circ\text{C}$
- Diodes measured before irradiation, after irradiation and after irradiation and standard annealing
- After irradiation diodes stored at $-20 \text{ }^\circ\text{C}$ to avoid uncontrolled annealing

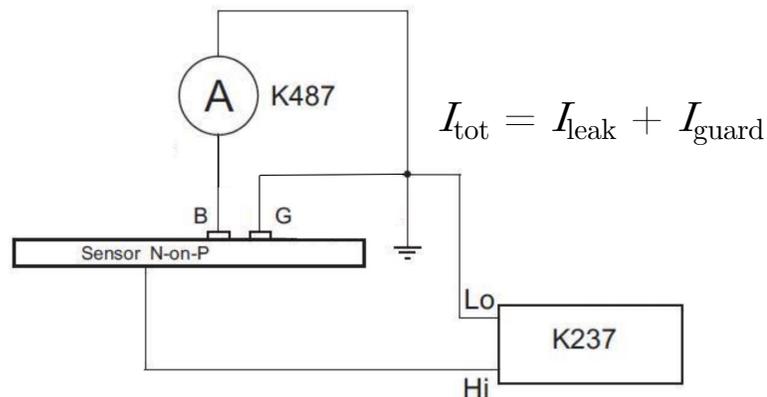
Standard Annealing

60 °C for 80 minutes

Full Depletion Voltage

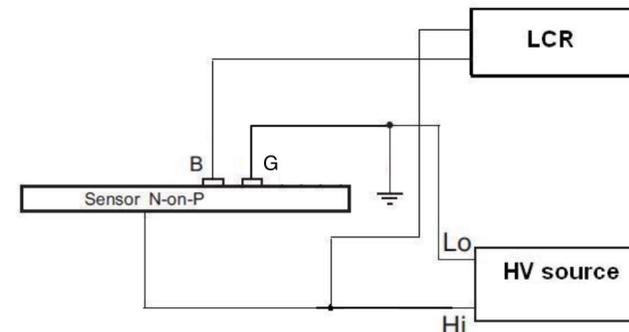
Determined from interpolation curves of measured CV characteristics

IV setup



By contacting guard ring we were able to separate leakage current I_{leak} from total current I_{tot}

CV setup



Guard ring grounded during all CV measurements

Irradiation

- Diodes irradiated by ^{60}Co gamma source in Charge Particle Equilibrium (CPE) box
- Fan used for cooling the irradiation area
 - Dose rate 19.45 krad/min in Si
 - Diameter of irradiation area 9 cm
 - Temperature up to 35 °C



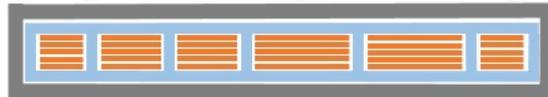
^{60}Co Terabalt, ÚJP Praha

CPE box

5 layers of diodes

Al 1 mm holder

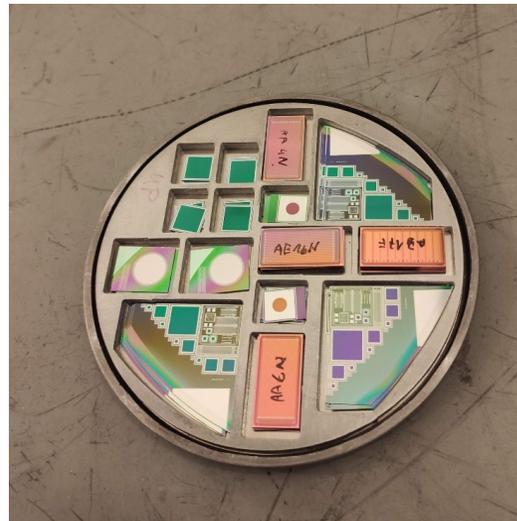
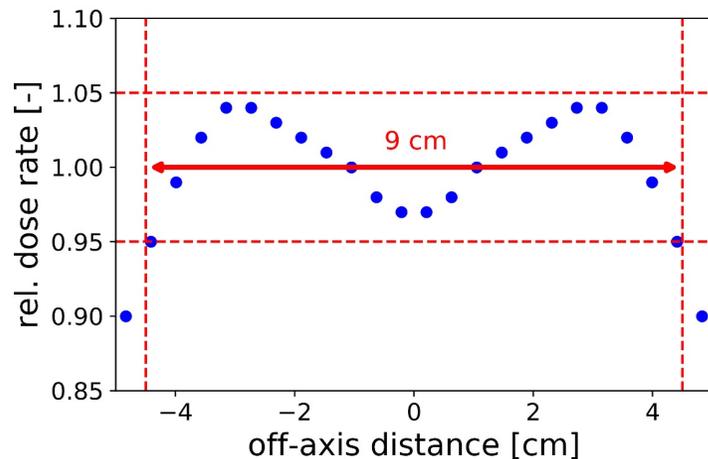
Pb 1.5 mm



} minimizes dose enhancement from low-energy scattered radiation by producing charged-particle equilibrium

Dose profile

^{60}Co -source to sample distance 3-4 cm

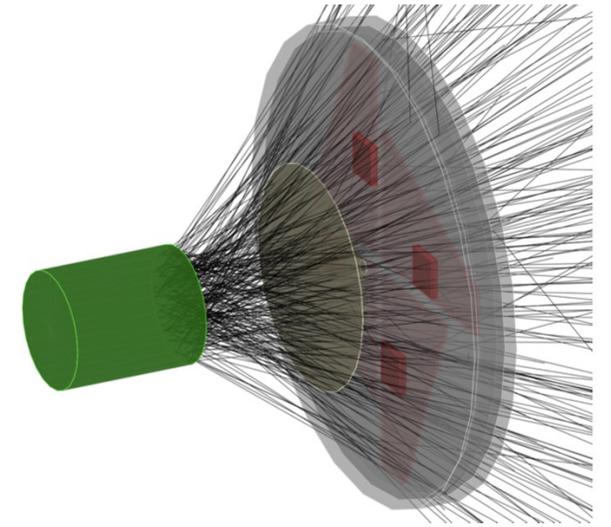
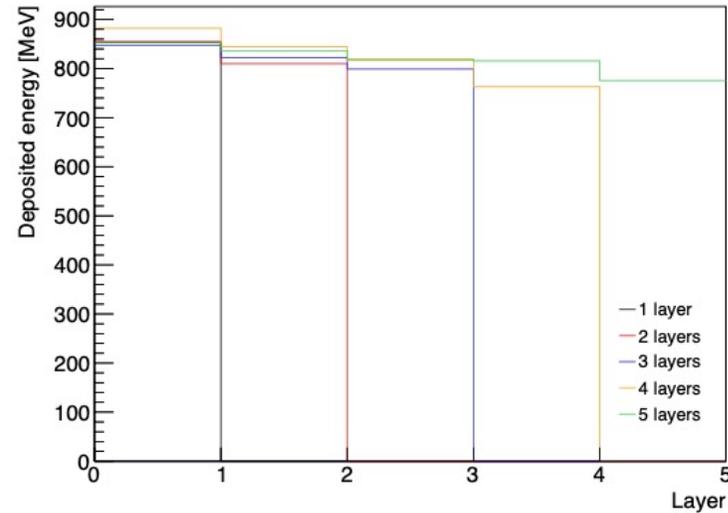


Dose [Mrad]	Dose [MGy]	Time of irradiation [h]	CNM	HPK	IFX
50	0.50	19.5	W03	W067 #2	W06W
75	0.75	29.2		W071 #3	
100	1.00	39	W02	W068 #2	01E
150	1.50	58.5	W01	W071 #1	01W
			W04		
198	1.98	77.2		W068 #1	W05W
216	2.16	84.2	W01		
250	2.50	97.5	W07	W071 #2	W07W
264	2.64	103		W068 #1	
300	3.00	117		W067 #1	
				W068 #3	
316	3.16	123.2	W07		W07W
366	3.66	142.7		W068 #3	

Irradiation

- Geant4 irradiation simulations
- Isotropic emission of $50 \cdot 10^6$ photons of energy 1.25 MeV

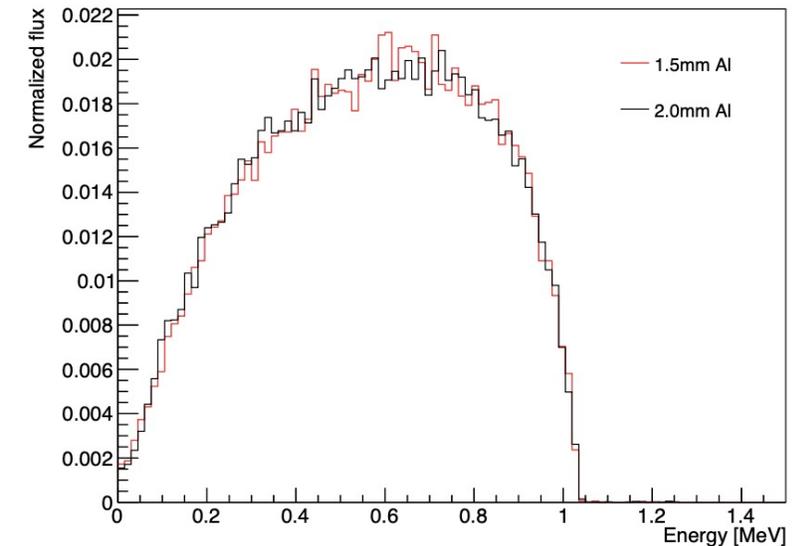
⇒ CPE box provides almost equal distribution of total deposited energy through all the layers of samples



Displacement damage caused ^{60}Co gamma is primarily caused by the interaction of Compton electrons with the maximum energy 1.2 MeV

- The minimum energy for production of clusters is ≈ 8 MeV
- The maximum recoil energy for the primary knock on Si atoms by Compton electron is ≈ 140 MeV
- The minimum electron energy needed for a single displacement resulting in Freknel pair is ≈ 260 keV

⇒ Damage caused by ^{60}Co gamma is exclusively caused by point defects.



CV Measurements of Unirradiated Diodes

- CNM diodes measured up to 250 V, HPK and IFX diodes measured up to 500 V, using frequency 1 kHz
- Assuming homogeneous space charge distribution, we can calculate resistivity ρ and effective doping concentration N_{eff} from measured FDV

Resistivity

$$\rho = \frac{d^2}{2\epsilon_0\epsilon_{\text{Si}}\mu_p F DV}$$

Effective doping concentration

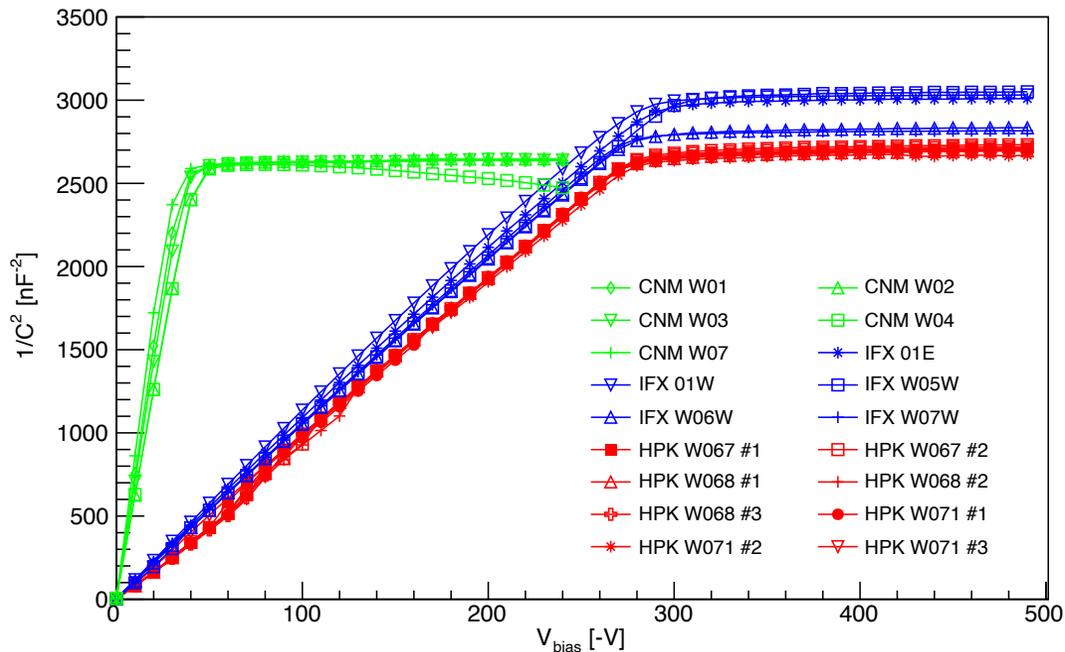
$$|N_{\text{eff}}| = \frac{2\epsilon_0\epsilon_{\text{Si}} F DV}{qd^2}$$

$$\epsilon_0 = 8.85 \cdot 10^{-12} \text{ F} \cdot \text{m}^{-1}$$

$$\epsilon_{\text{Si}} = 11.7$$

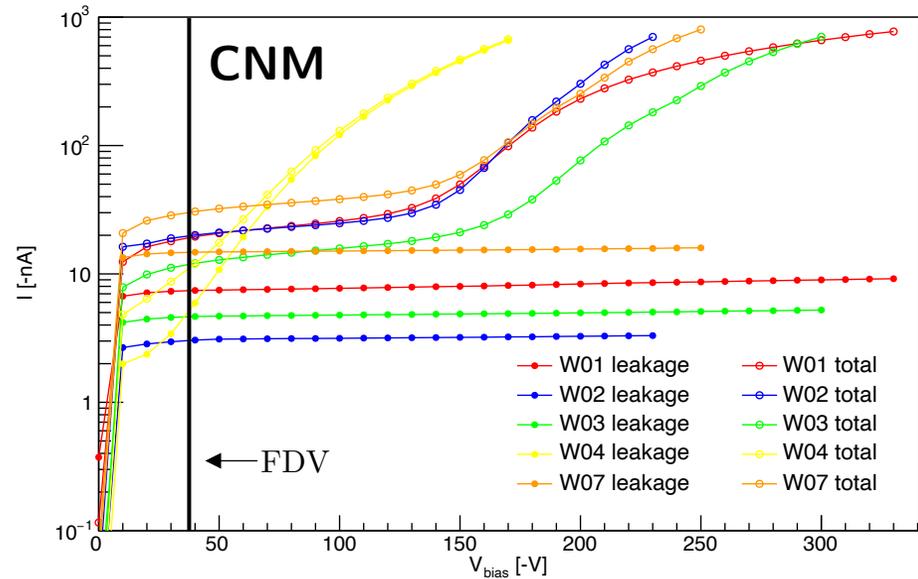
$$\mu_p = 450 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$$

$$q = 1.602 \cdot 10^{-19} \text{ C}$$



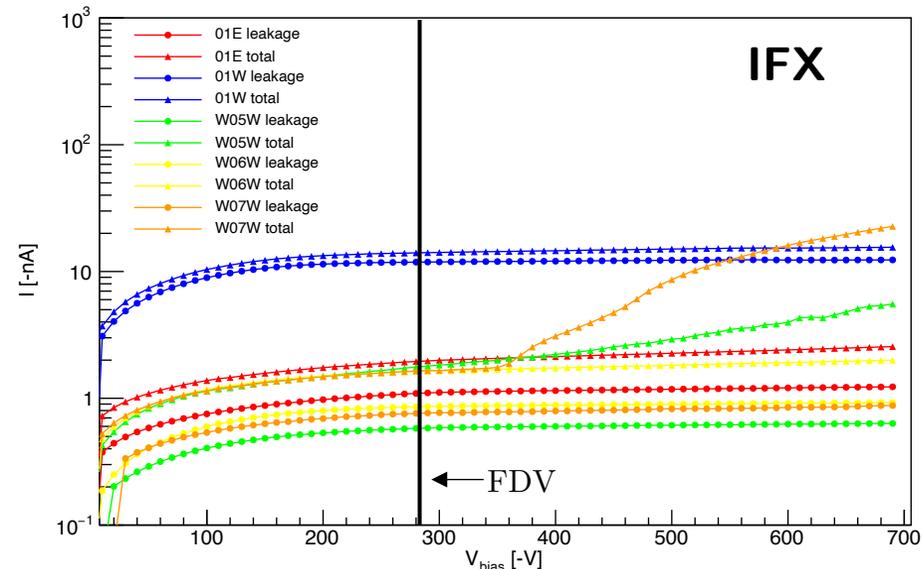
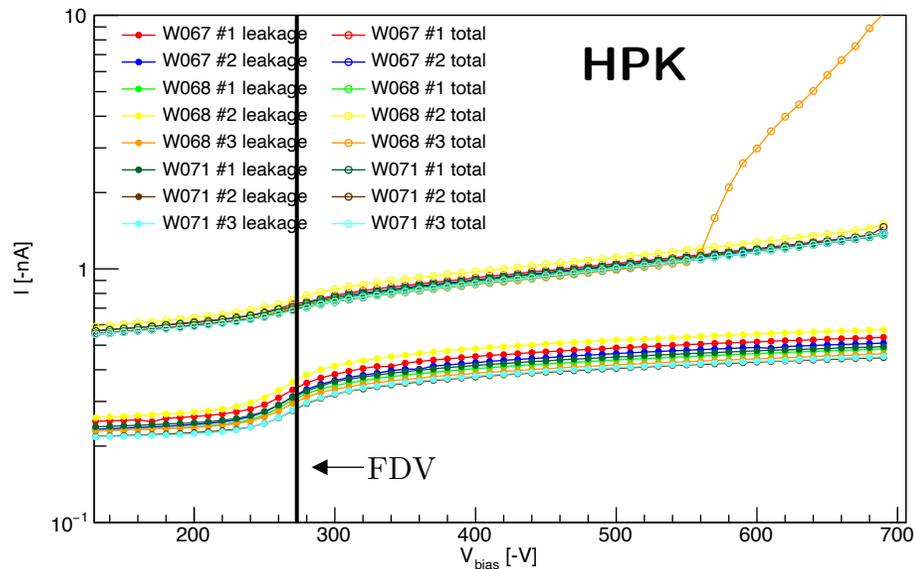
	CNM	HPK	IFX
Active thickness d	285 μm	290 μm	285 μm
Measured FDV	$(36.9 \pm 8.3) \text{ V}$	$(273.4 \pm 10.7) \text{ V}$	$(283.6 \pm 12.0) \text{ V}$
Resistivity ρ	$(23.975 \pm 4.012) \text{ k}\Omega \cdot \text{cm}$	$(3.301 \pm 0.001) \text{ k}\Omega \cdot \text{cm}$	$(3.077 \pm 0.001) \text{ k}\Omega \cdot \text{cm}$
Effective doping concentration $ N_{\text{eff}} $	$(0.59 \pm 0.13) \cdot 10^{12} \text{ cm}^{-3}$	$(4.20 \pm 0.16) \cdot 10^{12} \text{ cm}^{-3}$	$(4.52 \pm 0.19) \cdot 10^{12} \text{ cm}^{-3}$

IV Measurements of Unirradiated Diodes

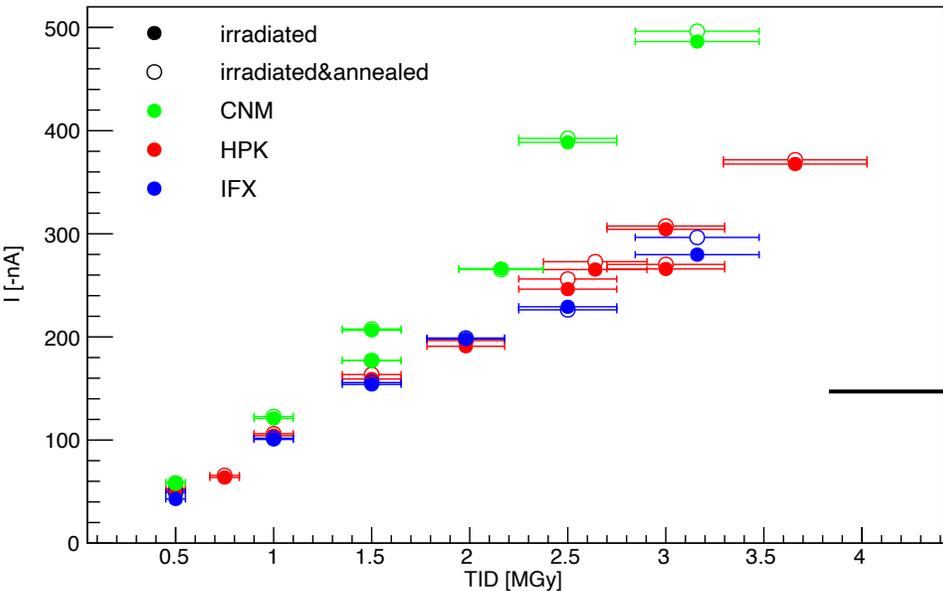
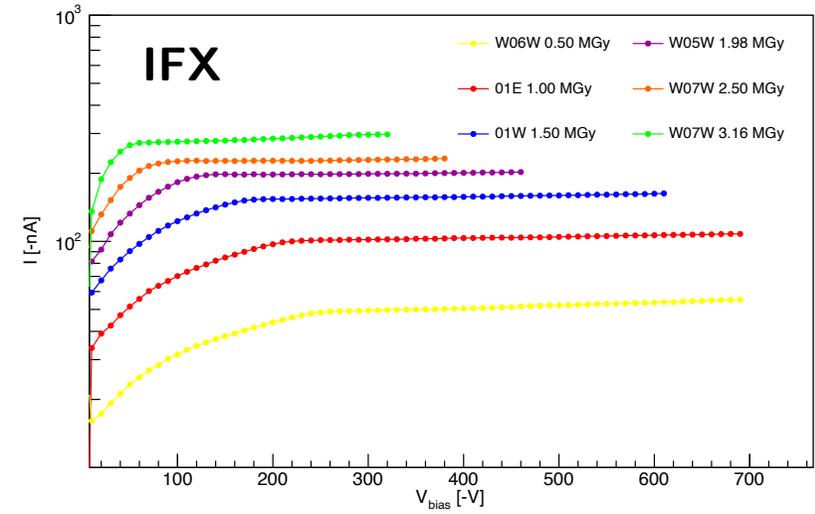
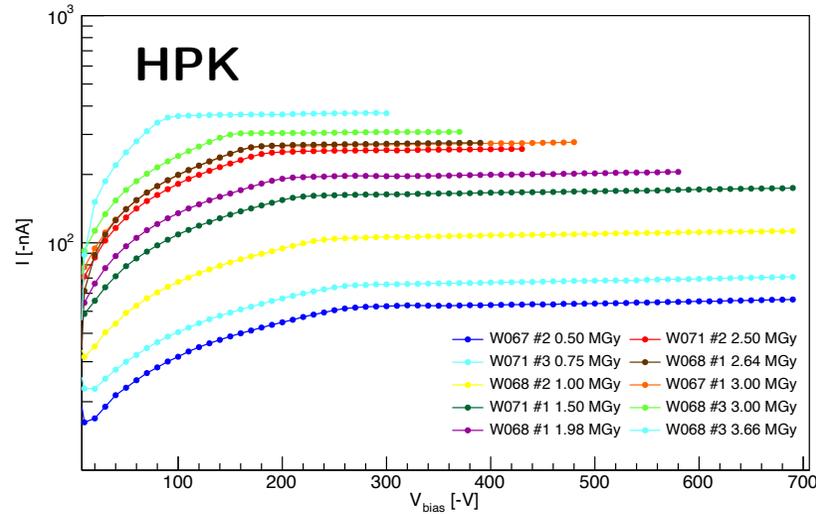
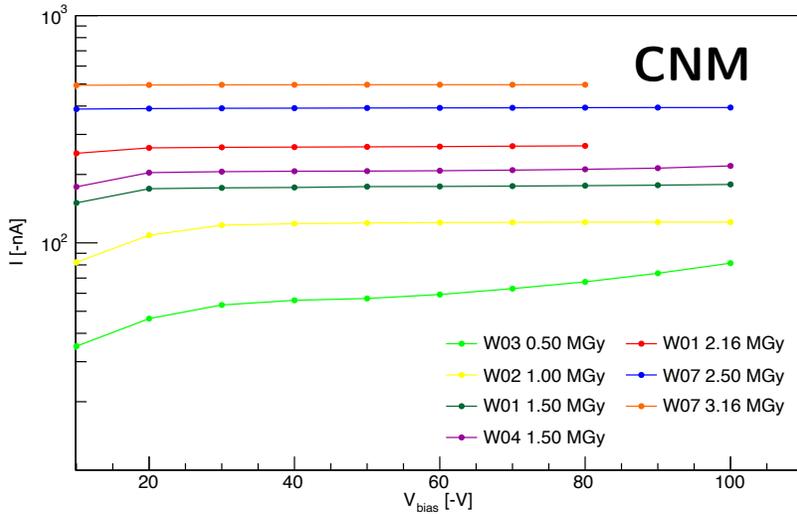


	CNM at 60 V	HPK at 300 V	IFX at 300 V
Leakage current I_{leak}	3-15 nA	0.3-0.5 nA	0.6-0.9 nA
Total current I_{tot}	10-30 nA	0.85-1.00 nA	1.6-2.0 nA

- Early breakdown of CNM **W04**
- IFX **01W** higher values of current than other IFX diodes
- HPK diodes have lowest values of leakage current



Leakage Current of Irradiated&Annealed Diodes

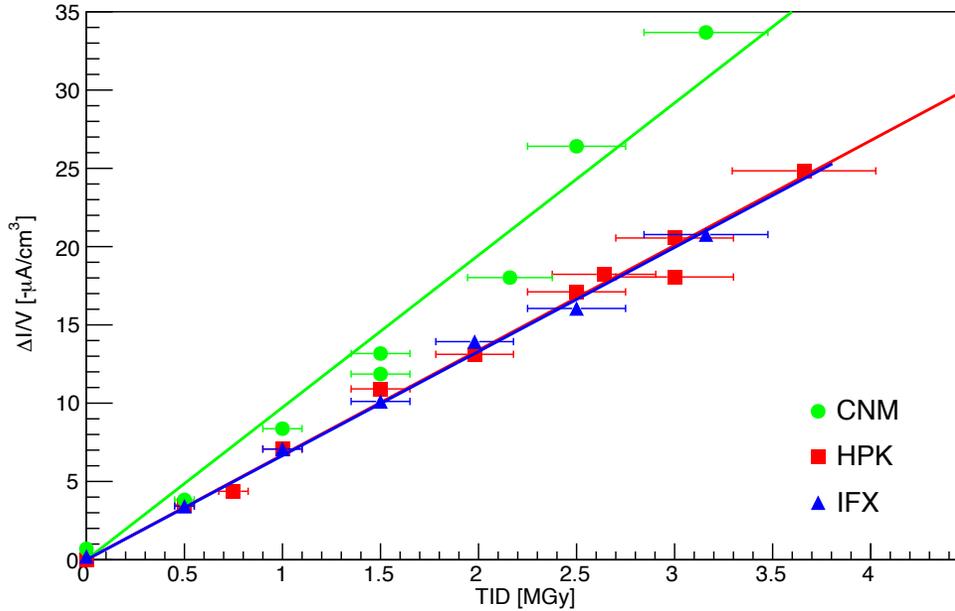


- Measured currents normalized to 20 °C
- Constant values of leakage current measured as expected
- Increasing values I_{leak} of with increasing TID

Change of I_{leak} after standard annealing was not observed.
 ⇒ Leakage current after gamma irradiation does not change after standard annealing.
 ⇒ Diodes were exposed to temperature up to 35 °C for \approx 100 hours and annealing took place during irradiation.

Leakage Current $\Delta I/V$ Dependence on TID after Annealing

- Leakage current increases up to the maximum TID linearly
- From the relation between $\Delta I/V$ and TID, we can determine the damage coefficient a

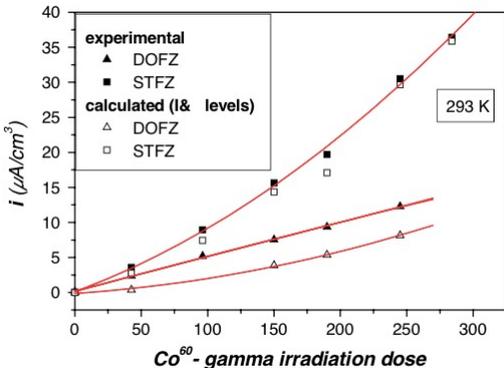


$$\frac{\Delta I}{V} = a \cdot TID$$

	a [$A \cdot cm^{-3} \cdot MGy^{-1}$]
CNM	$(9.73 \pm 0.43) \cdot 10^{-6}$
HPK	$(6.69 \pm 0.11) \cdot 10^{-6}$
IFX	$(6.65 \pm 0.09) \cdot 10^{-6}$

Diodes with the similar initial resistivity and therefore effective doping concentration – HPK&IFX, show the same degree of damage. CNM with higher initial resistivity and different effective doping concentration has higher damage coefficient.

	CNM unirradiated	HPK unirradiated	IFX unirradiated
Resistivity ρ	(23.975 ± 4.012) k $\Omega \cdot cm$	(3.301 ± 0.001) k $\Omega \cdot cm$	(3.077 ± 0.001) k $\Omega \cdot cm$



The results are in agreement with previous measurements of n-type standard float zone diodes.

I. Pintilie et al., NIM A 514 (2003)

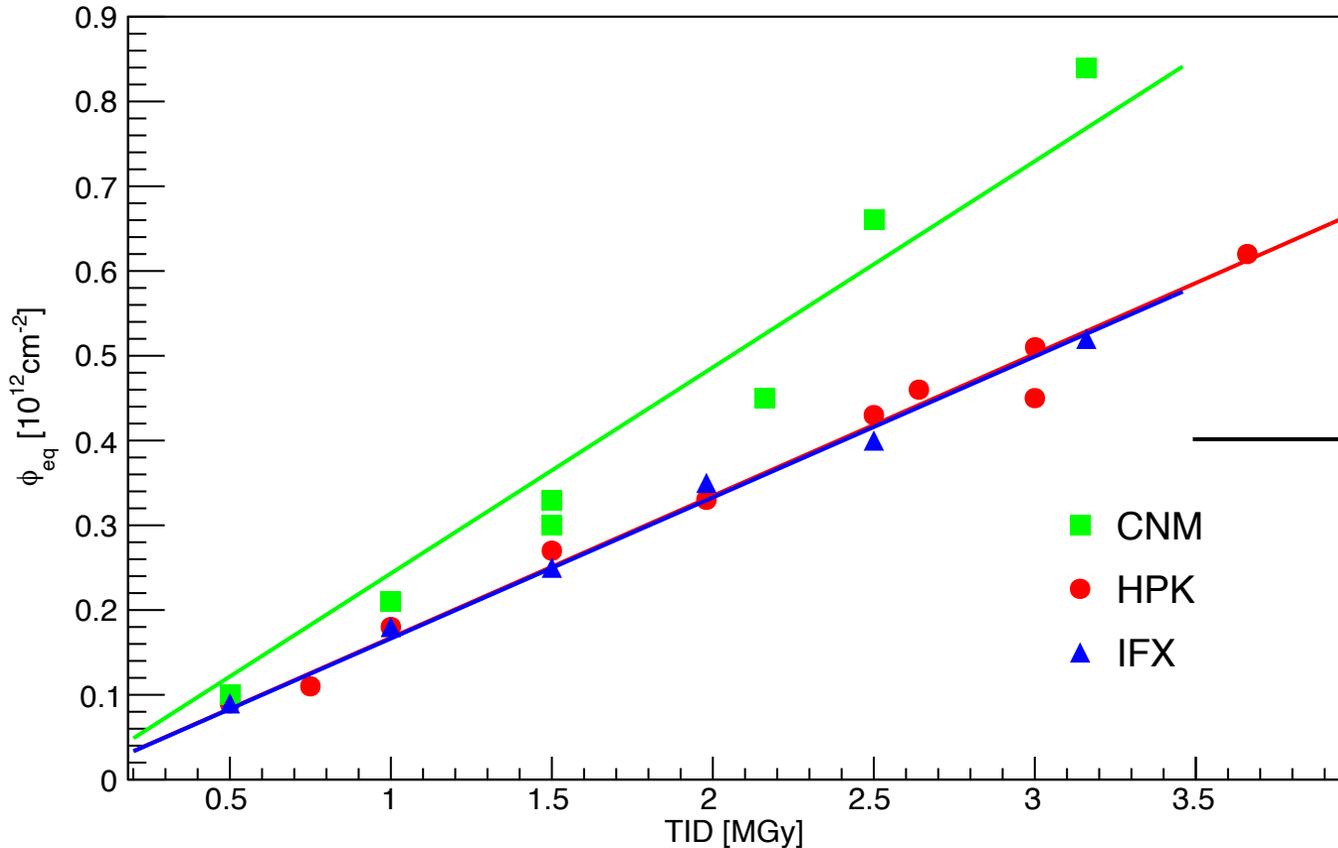
TID vs. Φ_{eq} after Annealing

Assuming increasing leakage current with TID that is caused by displacement damage, we can estimate equivalent fluence Φ_{eq} from damage parameter α Moll 2018

$$\frac{\Delta I}{V} = \alpha \cdot \Phi_{eq}$$

$$\alpha = (3.99 \pm 0.03) \cdot 10^{-17} \text{ A} \cdot \text{cm}^{-1}$$

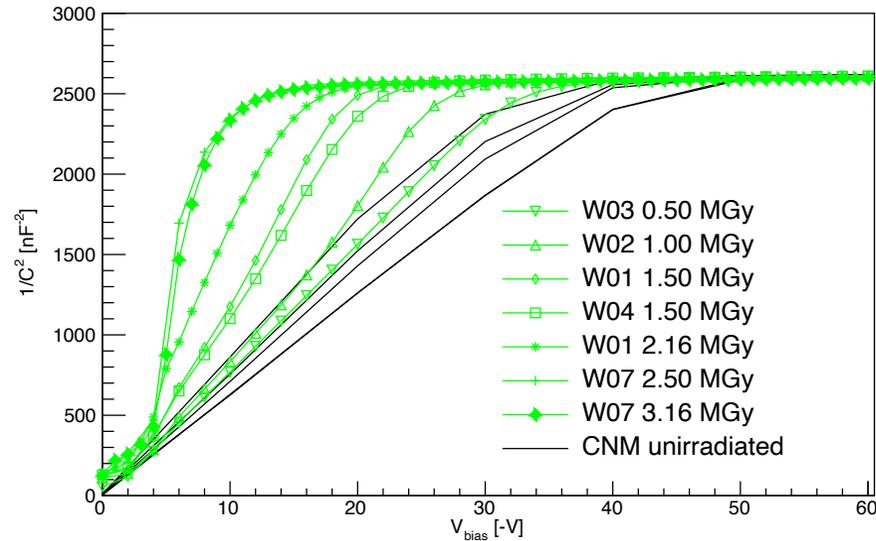
for currents measured at 20 °C after annealing (80 min for 60 °C)



1 MGy = $2.4 \cdot 10^{11} \text{ cm}^{-2}$ for CNM diodes
1 MGy = $1.7 \cdot 10^{11} \text{ cm}^{-2}$ for HPK&IFX diodes

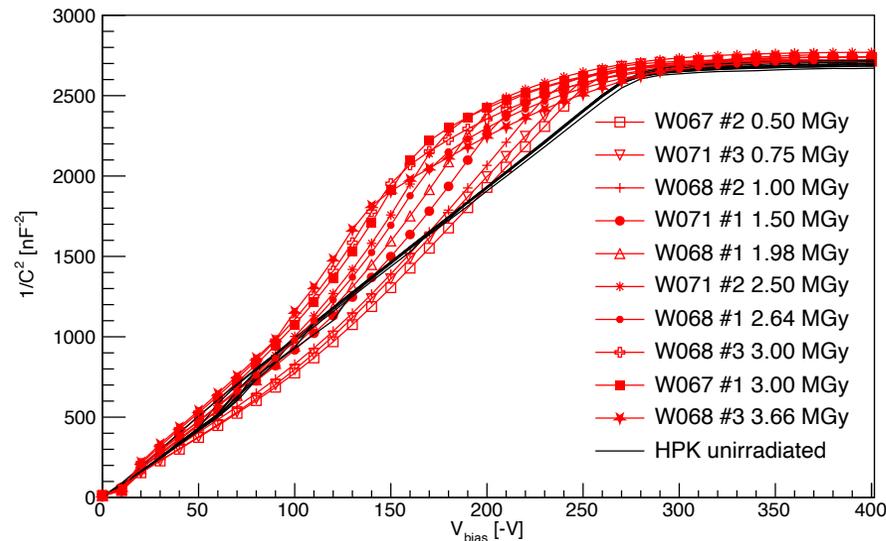
CV Measurements of Irradiated & Annealed Diodes

CV CNM 100 kHz annealed

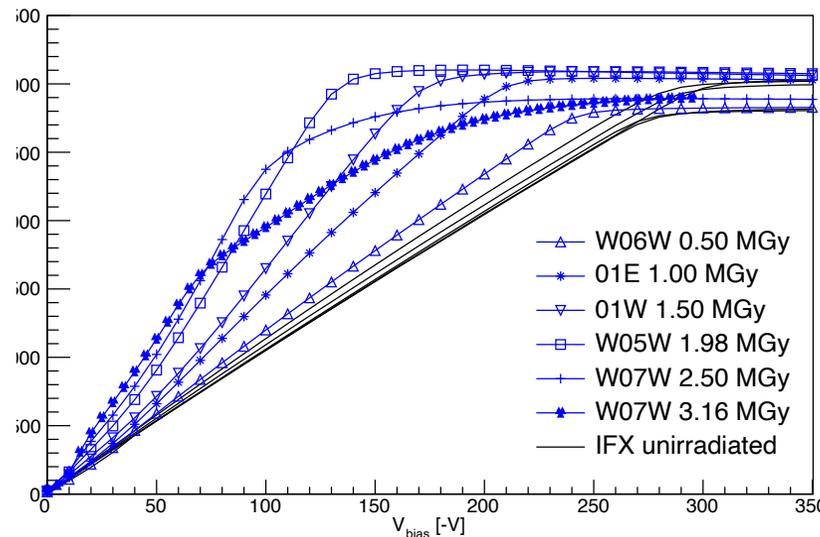


Observed change in CV characteristics with increasing TID
 \Rightarrow Significant change of effective doping concentration
 N_{eff} with TID.

CV HPK 10 kHz annealed

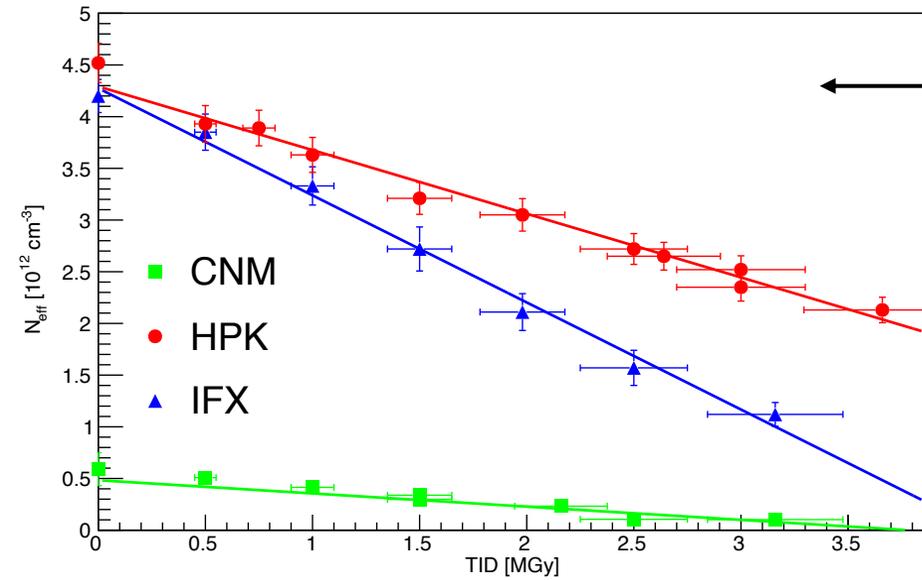


CV IFX 100 kHz annealed



Test frequency determined from measured dependencies of capacitance on test frequency (measurements available in backup slides).

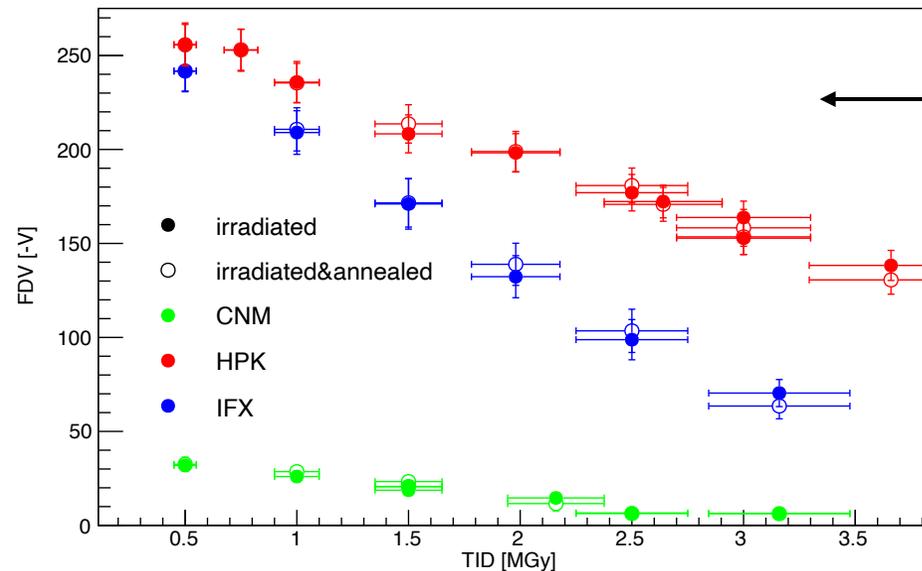
FDV Dependence on TID



N_{eff} and therefore FDV significantly linearly decreases with increasing TID

	CNM	HPK	IFX
Maximum TID	3.16 MGy	3.66 MGy	3.16 MGy
Decrease in FDV	83 %	49 %	75 %

The minimum of N_{eff} is not observed up to the maximum TID



Comparison of FDV values before and after annealing
No dependence of FDV on annealing observed.

Conclusions

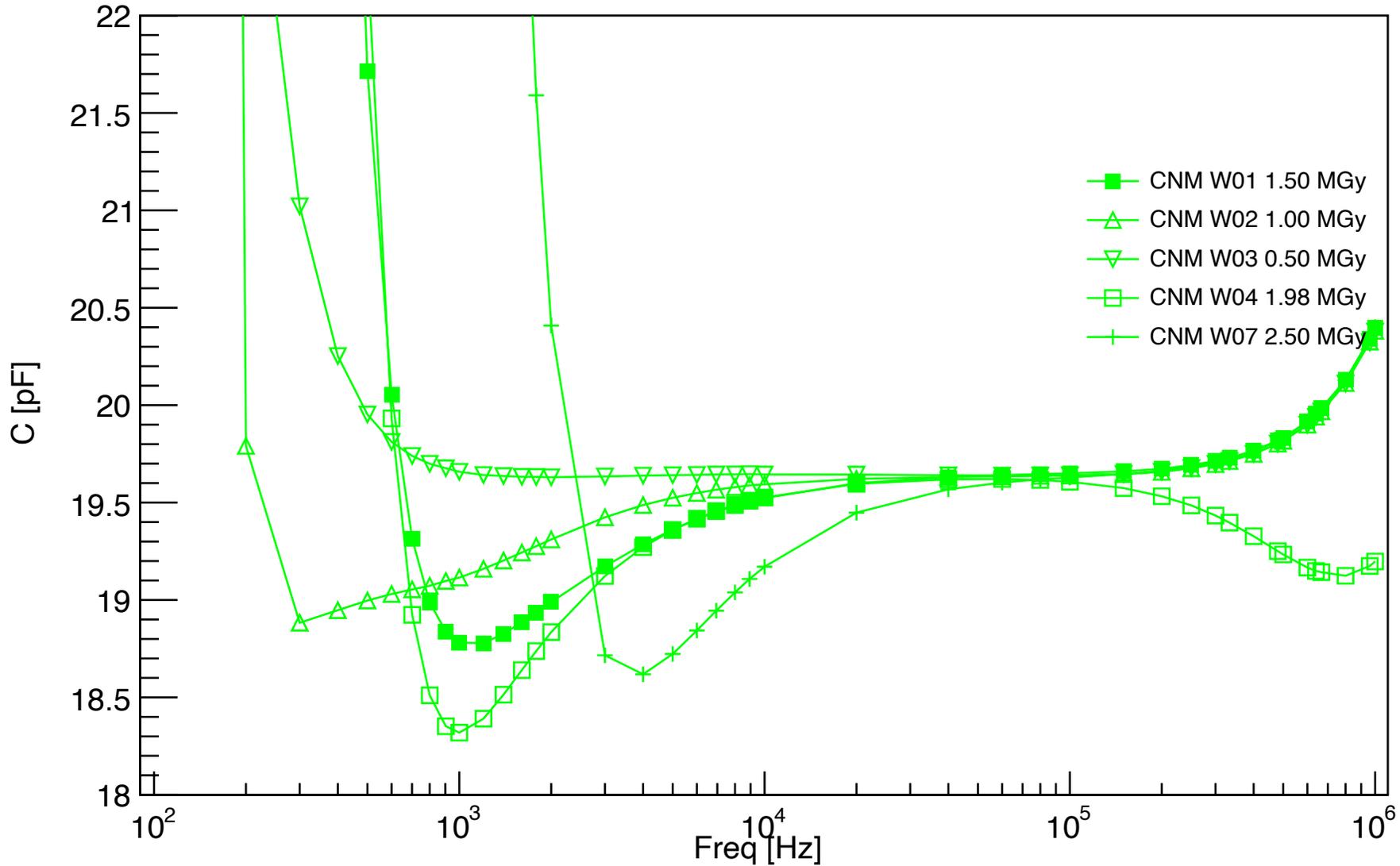
- The effects of gamma irradiation on p-type silicon diodes were studied.
- The diodes had comparable active areas and thickness but different initial silicon resistivities and oxygen concentrations. Thanks to the contactable guard ring we were able to separate I_{leak}
- Diodes were irradiated up to ≈ 3 MGy by ^{60}Co and then annealed at $60\text{ }^\circ\text{C}$ for 80 minutes.
- Annealing effect in gamma irradiated diodes was not observed.
- Leakage current increases linearly with increasing TID by $6.7 \cdot 10^{-6}$ A/cm³/MGy for HPK&IFX diodes and by $9.7 \cdot 10^{-6}$ A/cm³/MGy for CNM diodes.
- N_{eff} and therefore FDV significantly linearly decreases with increasing TID and the minimum is not observed up to the maximum TID ≈ 3 MGy.

Future plans

- Further studies of field distribution and charge collection by TCT method required.
- Irradiation up to higher maximum TID planned.
- Improvement of cooling during the irradiation needed to avoid uncontrolled annealing.
- Study should be repeated with samples with known oxygen concentration.

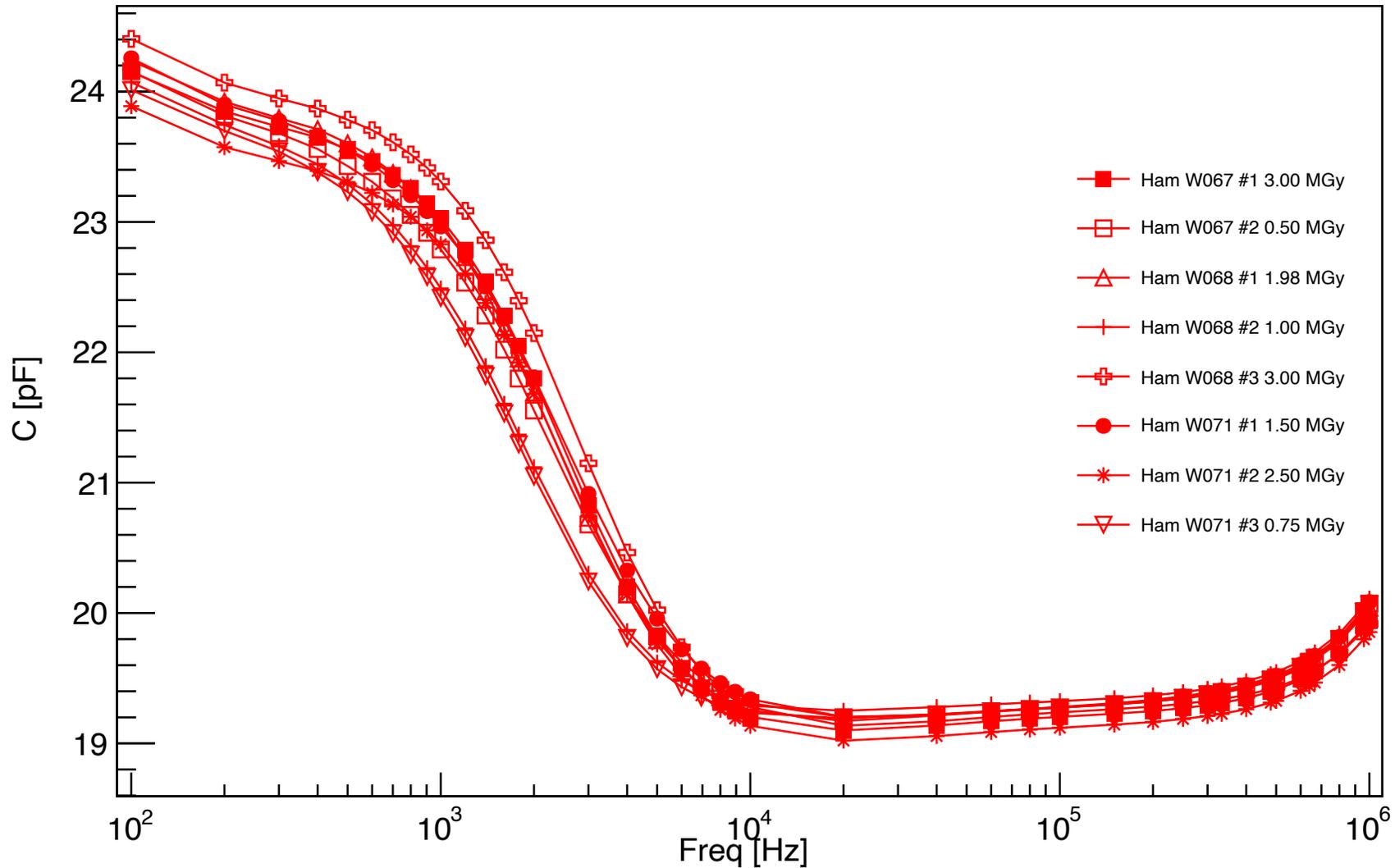
Back up

Capacitance Dependence on Measuring Frequency of CNM Irradiated and Annealed Diodes @ 60 V



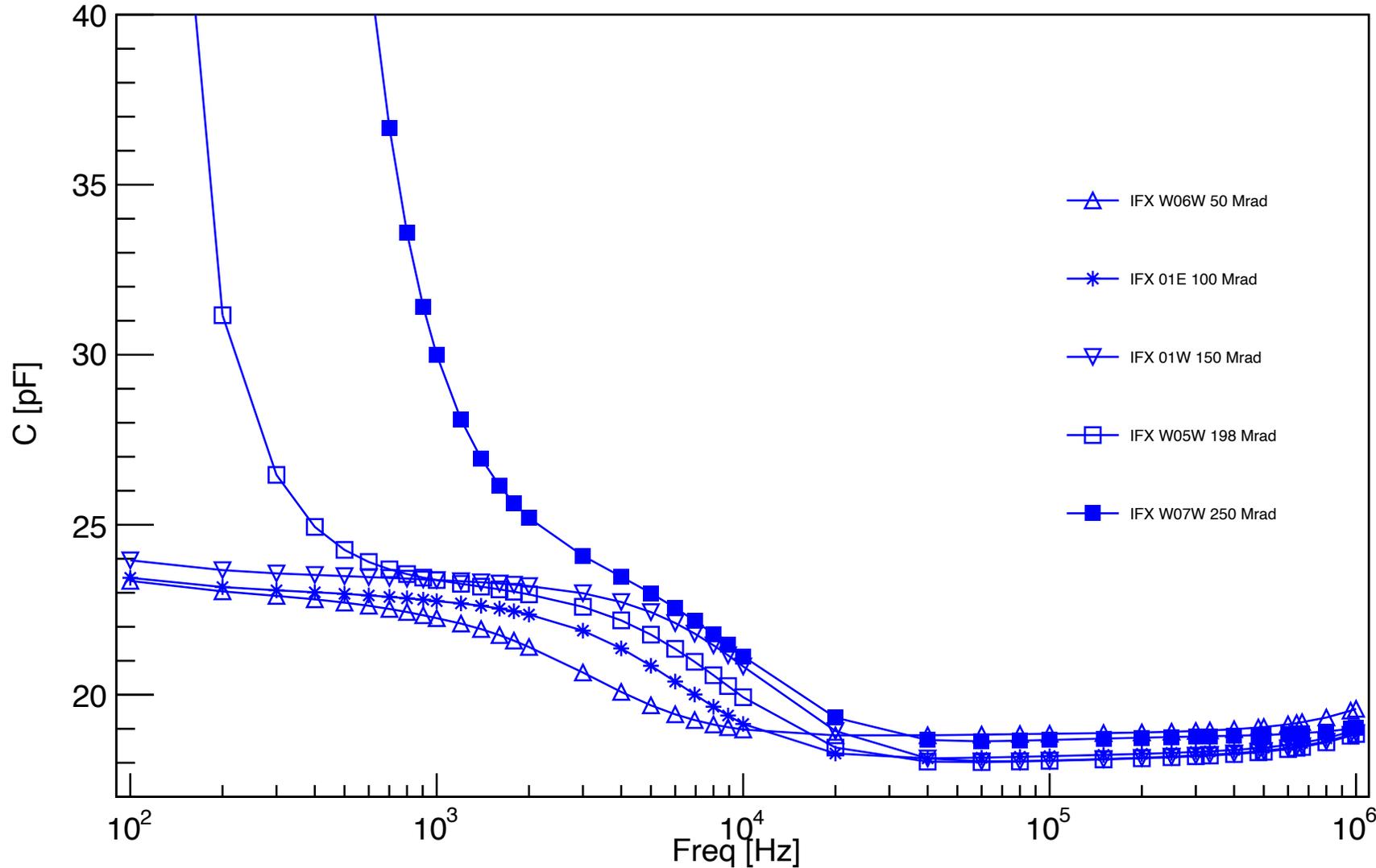
- Chosen measuring frequency 100 kHz

Capacitance Dependence on Measuring Frequency of HPK Irradiated and Annealed Diodes @ 300 V



- Chosen measuring frequency 100 kHz

Capacitance Dependence on Measuring Frequency of IFX Irradiated and Annealed Diodes @ 300 V



- Chosen measuring frequency 100 kHz

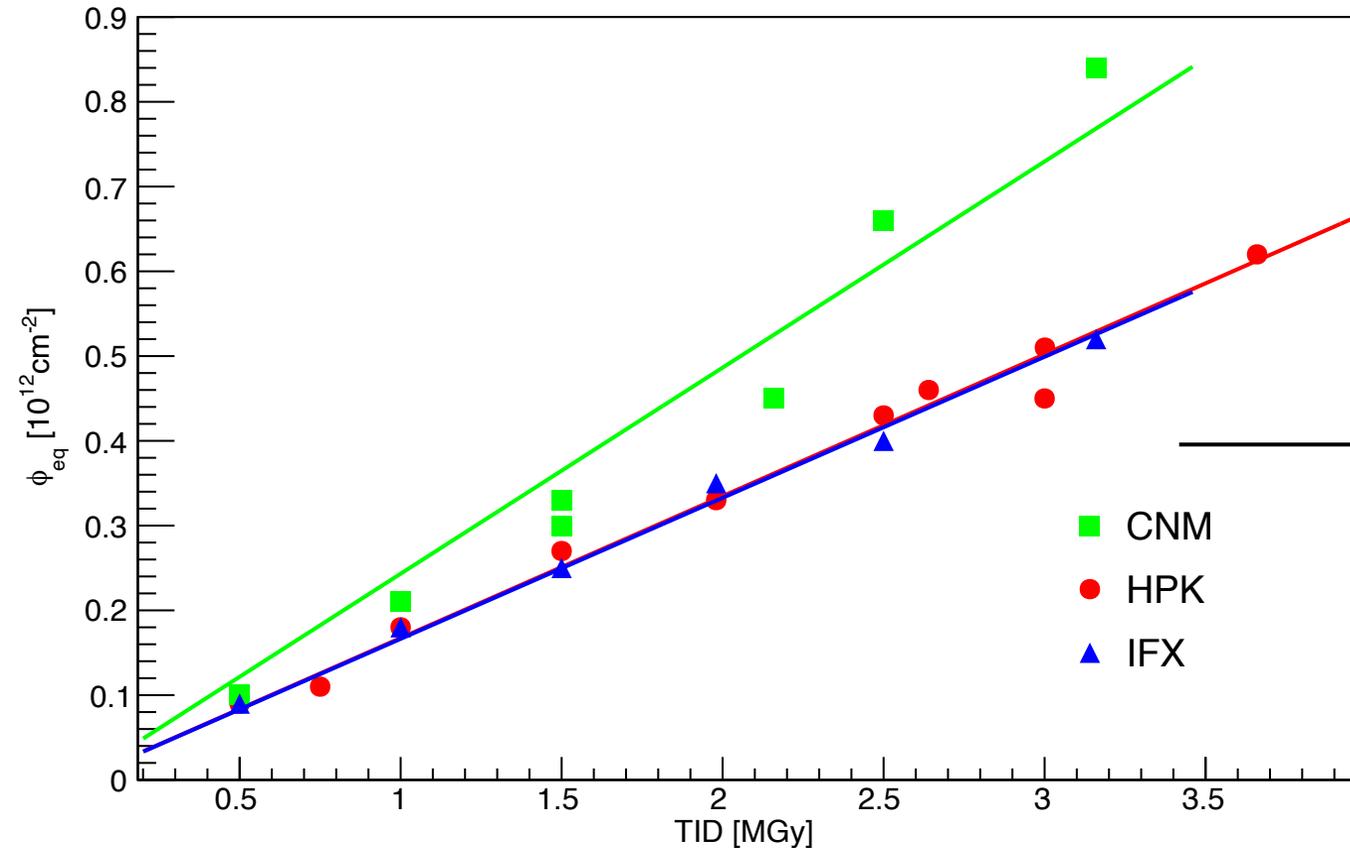
TID vs. Φ_{eq} after Annealing

Assuming increasing leakage current with TID that is caused by displacement damage, we can estimate equivalent fluence Φ_{eq} from damage parameter α Moll 2018

$$\frac{\Delta I}{V} = \alpha \cdot \Phi_{eq}$$

$$\alpha = (3.99 \pm 0.03) \cdot 10^{-17} \text{ A} \cdot \text{cm}^{-1}$$

for currents measured at 20 °C after annealing (80 min for 60 °C)



1 MGy = $2.4 \cdot 10^{11} \text{ cm}^{-2}$ for CNM diodes

1 MGy = $1.7 \cdot 10^{11} \text{ cm}^{-2}$ for HPK&IFX diodes

1 MGy = $9.3 \cdot 10^{12} \text{ cm}^{-2}$

G. Lindstroem et al.,
Journal of Optoelectronics Vol.4 (2004)

1 MGy = $4.8 \cdot 10^{11} \text{ cm}^{-2}$

Z. Li et al., IEEE Transactions
on Nuclear Science Vol. 44 (1997)